# The New ACI Code 440.11-22

Vicki L. Brown[1](✉), Will Gold[2], and Carol Shield[3]

[1] Widener University, Chester, PA 19013, USA
`vlbrown@Widener.edu`
[2] American Concrete Institute, Farmington Hills, MI 48331, USA
[3] University of Minnesota, Vadnais Heights, MN 55127, USA

**Abstract.** The American Concrete Institute (ACI) recently published ACI Code 440.11-22 *Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars.* This new Standard, which is dependent on ACI 318-19 *Building Code Requirements for Structural Concrete,* mandates minimum requirements for materials, design, and detailing of structural concrete buildings reinforced with GFRP bars that conform to ASTM D7957 and can be adopted by building codes or referenced by design professionals and building officials. ACI Code 440.11 covers non-prestressed concrete construction for structures that do not require a fire-resistance rating, and includes requirements for strength, serviceability, durability, structural analysis methods, development and splicing of reinforcement, and methods to evaluate the strength of existing structures. The Commentary to the Code provides explanation of differences in design between GFRP-reinforced concrete and steel-reinforced concrete. This paper provides an overview of ACI Code 440.11, discussing its applications and limitations and how other standards from ACI and ASTM provide the foundation on which the new Code has been developed. Differences from the requirements given in ACI 318 that account for both the lower stiffness of GFRP reinforcement and for the lack of a yield point in GFRP bars are highlighted, with a focus on how flexural strength and serviceability requirements are affected.

**Keywords:** codes · design · design guidelines · GFRP · structural concrete

## 1 Introduction

The American Concrete Institute (ACI) recently published a design standard for glass fiber-reinforced polymer (GFRP) reinforced concrete. ACI's *Building Code Requirements for Structural Concrete Reinforced with GFRP Bars* [1], herein referred to as Code 440.11, mandates minimum requirements for materials, design, and detailing of structural concrete buildings and other structures reinforced with GFRP bars that conform to ASTM D7957-22 [2]. Corrosion resistance, electromagnetic neutrality, low thermal conductivity, light weight, and ease of cutting make GFRP an attractive alternative to steel reinforcement for applications such as bridge decks, seawalls, MRI rooms, high voltage transformer pads, parking garages, and mining applications. Development of Code 440.11 followed the American National Standards Institute (ANSI) approved consensus

A. Ilki et al. (Eds.): *fib* Symposium 2023, LNCE 349, pp. 1837–1846, 2023.
https://doi.org/10.1007/978-3-031-32519-9_184

process. As a standardized document, Code 440.11 can be adopted by model building codes or referenced by designers and building officials. The International Code Council voted in 2022 to adopt Code 440.11 by reference into the 2024 edition of the International Building Code (IBC) for design and construction of GFRP-reinforced concrete. Code 440.11 thus joins ACI 318 *Building Code Requirements for Structural Concrete* [3] as the structural codes by which the IBC mandates the design and construction of reinforced concrete (RC) structures. In the United States, the power to regulate design and construction of buildings belongs to the government of individual states, counties, cities and townships, with most of these jurisdictions adopting some version of the IBC as their local building code. As a result, the inclusion of Code 440.11 in IBC 2024 will broaden the acceptance of GFRP-RC in the U.S. construction industry. This paper provides an overview of ACI Code 440.11, highlighting design with GFRP reinforcement for flexural strength and serviceability that will be different from design with steel reinforcement per ACI 318.

## 2 Transitioning from Guide to Code

The ACI *Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars* [4] was first published over two decades ago. Work to develop the design approaches recommended in the *Guide* into a GFRP-RC design code in mandatory language, dependent to the ACI 318 design standard for design and construction of steel-reinforced concrete, began in earnest in early 2015 and culminated in the publication of Code 440.11 in September 2022. The new Code mirrors ACI Code 318-19, with provisions for designing GFRP-RC beams, one-way and two-way slabs, columns, walls, connections, and foundations. Design of GFRP-RC members generally follows the same philosophy used for steel-RC members, although with adjustments to design requirements to account for both the lower stiffness of GFRP reinforcement and the lack of a yield point in GFRP bars. The code development process required new research and validation before Code 440.11 could address topics that are not covered in the ACI 440.1R-15 *Guide*, such as torsion, design of columns, and connections.

This initial version of Code 440.11 does not apply to members in any structure assigned to Seismic Design Categories (SDC) D, E, or F; and use in structures assigned to SDC B or C is limited to members that are not part of the lateral-load-resisting system. Other topics that are not addressed in this first version of the Code include prestressed construction, lightweight concrete, connections of precast members, diaphragms, deep beams, drilled piers and caissons, brackets and corbels, methods for designing discontinuity regions using strut-and-tie theory where section-based methods do not apply, shear friction, and anchoring to concrete. The design of "hybrid" members with mixed types of reinforcement is not within the scope, although Code 440.11 can be used for design of GFRP-RC members in structures that also include members not reinforced with GFRP.

As GFRP bars can lose bond with concrete due to softening of the resin if used in conditions that have service temperatures approaching the bars' glass transition temperature [5], the Code specifies that GFRP reinforcement not be used when service temperatures are greater than 15 °C below the glass transition temperature. GFRP bars that have glass transition temperatures in excess of 120 °C are commercially available. Because the mechanical and bond properties of GFRP bars are more negatively impacted at elevated temperatures than are steel bars, and reports from ASTM E119 fire tests on GFRP-RC members are not yet available, Code 440.11 is only applicable where fire-resistance ratings are not required or where approved by the building official under alternative means and methods provisions. Recommendations for increasing the fire resistance of GFRP-RC members have been included in the Commentary to Code 440.11.

Table 1 shows the Code 440.11 chapter organization, which is consistent with ACI 318-19. However, Code 440.11 does not include some chapters that are addressed in ACI 318-19; specifically, Chapter 12: Diaphragms, Chapter 17: Anchoring to Concrete, Chapter 18: Earthquake-Resistant Structures, and Chapter 23: Strut-and-Tie Method have been omitted from this version of the Code. These chapters are expected to be included in future versions of Code 440.11 as additional research becomes available. Chapter 14: Plain Concrete from ACI 318-19 is also not included, and will not be covered in future Code versions because it is not related to design with GFRP reinforcement. Chapter numbering remains consistent with ACI 318-19.

**Table 1.** ACI Code 440.11-22 Chapters

| Chapter | Title | Chapter | Title |
|---|---|---|---|
| 1 | General | 13 | Foundations |
| 2 | Notation & Terminology | 15 | Beam-Column & Slab-Column Joints |
| 3 | Referenced Standards | 16 | Connections between Members |
| 4 | Structural System Requirements | 19 | Concrete Design & Durability |
| 5 | Loads | 20 | GFRP Reinforcement Properties |
| 6 | Structural Analysis | 21 | Strength Reduction Factors |
| 7 | One-way Slabs | 22 | Sectional Strength |
| 8 | Two-way Slabs | 24 | Serviceability Requirements |
| 9 | Beams | 25 | Reinforcement Details |
| 10 | Columns | 26 | Construction Documents & Inspection |
| 11 | Walls | 27 | Strength Evaluation of Existing Structures |

## 3 Related Standards and Guides

In addition to the ACI 440.1R-15 *Guide*, ACI Code-318, and the ASTM D7957 GFRP bar specification discussed in the previous section, Code 440.11 builds on a number of additional standards and test methods specific to GFRP-RC design and construction. Most notable is ACI SPEC 440.5-22 [6], which was first published in 2008 and covers the specifics of concrete construction with GFRP reinforcement. SPEC-440.5 is intended to be applied in conjunction with the ACI general concrete construction specification, ACI SPEC 301-20 [7]. ACI SPEC 440.5 replaces SPEC 301 Section 3 covering steel reinforcement, while all other sections of ACI SPEC 301 apply equally to steel and GFRP reinforced concrete. A GFRP-RC design standard would not have been viable without a GFRP-RC construction specification or a GFRP bar specification, which was first published in 2017. And the bar specification would not have been viable prior to development of ASTM standard test methods for GFRP bar properties, including ASTM D7205 (tensile properties) [8], ASTM D7617 (transverse shear strength) [9], ASTM D7705 (alkali resistance) [10], ASTM D7913 (bond strength) [11], and ASTM D7914 (bent bar strength) [12]. Initial versions of those standard test methods were first published between 2006 and 2014. The Masonry Society has included masonry reinforced with GFRP bars in Appendix D of its design standard *Building Code Requirements for Masonry Structures* [13].

## 4 Major Differences in Design from ACI Code 318-19

### 4.1 GFRP Material Properties that Affect Design and Analysis

GFRP bars have higher tensile strength but are not as stiff as steel. GFRP is elastic up to failure and the lack of a yield point has implications for seismic areas, as plastic hinge regions associated with moment redistribution due to bar yielding do not form in GFRP-RC members. GFRP bar strength also varies by bar size. The anisotropic behavior of GFRP means unidirectional bars have high strength in the fiber direction but low transverse shear strength and dowel action. GFRP bars can be fabricated with bends, but they cannot be field bent and the tensile strength at bends is reduced to about 60% of the strength of the straight bar.

Moment redistribution is smaller in GFRP-RC flexural members than it is in steel-RC, and is mainly the result of concrete cracking as the GFRP does not yield. If steel is used as reinforcement, most of the moment redistribution is the result of yielding, although some moment redistribution occurs prior to yield from the difference in flexural stiffness due to cracking along the member. Moment redistribution in excess of 18% in continuous GFRP-RC beams has been reported [20]. The observed moment redistribution was attributed to the relatively low modulus of elasticity of the GFRP bars making it possible to achieve the required section deformability for moment redistribution to occur, although not to the same extent as in continuous steel-RC members. Thus, use of the Direct Design (DDM) and Equivalent Frame Methods (EFM) for analysis of two-way slabs is permitted in Code 440.11; the Code does not allow moment redistribution beyond that required for DDM/EFM.

The lower modulus of GFRP bars causes increased cracking in GFRP-RC members and leads to changes in modeling assumptions for the moments of inertia used in elastic analysis in Code 440.11. The $0.25I_g$ for slabs, $0.35I_g$ for beams, and $0.7I_g$ for columns permitted for factored-load analysis in ACI 318-19 have been reduced to $0.15I_g$ for slabs and beams, and $0.4I_g$ for columns in Code 440.11, although these values are permitted to be increased by 1.5 for service-load analysis in contrast to the 1.4 factor used in 318-19. The effective column stiffness $EI_{eff}$ in the equations for computing stability properties in the moment magnification methods has been reduced from $0.4EI_g$ in ACI 318-19 to $0.24EI_g$ in Code 440.11. Limits on slenderness ratios for a column to be classified as short are also more restrictive in Code 440.11 when compared with ACI 318-19, based on a study conducted by Mirmiran [21] that recognized that use of lower-stiffness GFRP bars makes columns more susceptible to slenderness effects. Based on the parametric study, the slenderness ratio limit of 22 used for steel-RC columns bent in single curvature has been reduced to 17 for GFRP-RC columns in Code 440.11.

## 4.2 Differences in Design for Flexural Strength and Serviceability

Deflections and crack control requirements usually govern GFRP-RC beam design. Instead of taking the approach to design for strength and check for serviceability as is done when sizing a concrete cross section with steel reinforcement, a more suitable approach for design of GFRP-RC is to select a reasonable cross section for the given loads and span based on flexural serviceability requirements and then to verify that flexural strength is adequate. Unlike ACI 318 which permits both direct (based on computing deflections) and indirect (based on mandating minimum member thickness) methods for deflection control, Code 440.11 permits only the direct method. However, the approach to computing deflections is the same for GFRP-RC and steel-RC, using identical deflection limits. Both codes permit immediate deflections to be calculated using elastic methods or formulas, with effects of cracking considered through the use of an effective moment of inertia $I_e$ that is based on a weighted average of flexibility. The forms of the $I_e$ equation for GFRP and steel reinforcement - while not identical - are similar, as can be seen by comparing Eq. (1) for $I_e$ from ACI 318 to Eq. (2) for $I_e$ from Code 440.11.

$$I_{e,steel} = \frac{I_{cr}}{1 - \left(\frac{2/3M_{cr}}{M_a}\right)^2 \left(1 - \frac{I_{cr}}{I_g}\right)} \tag{1}$$

$$I_{e,GFRP} = \frac{I_{cr}}{1 - \gamma\left(\frac{0.8M_{cr}}{M_a}\right)^2 \left(1 - \frac{I_{cr}}{I_g}\right)} \tag{2}$$

where $M_a$ = maximum moment from service loads, $M_{cr}$ = cracking moment, $I_g$ = gross moment of inertia neglecting concrete, $I_{cr}$ = moment of inertia of cracked section transformed to concrete, and $\gamma$ is a factor that accounts for variation in stiffness over the member length. The reduction factor applied to $M_{cr}$ increases for GFRP-RC because of the lesser restraint that can reduce the cracking moment that occurs in GFRP-RC compared to sections with steel reinforcement.

GFRP reinforcement is also less effective at controlling creep than is steel reinforcement; thus, the compression reinforcement ratio $\rho'$ that appears in the denominator of the long-term deflection multiplier $\lambda_\Delta$ in ACI 318, as shown in Eq. (3), is removed from the $\lambda_\Delta$ multiplier in Code 440.11, as seen in Eq. (4). Experimental studies [14–16] have shown that the time-dependent deflection, when considered as a multiple of the instantaneous deflection, is smaller for GFRP-RC than for steel-RC. As a result, the value of the time-dependent factor $\xi$ for GFRP-RC in Eq. (4) is reduced by 60% to calculate additional deflections due to long-term effects; however, the procedure itself in which the $\lambda_\Delta$ multiplier is applied to elastic deflections from sustained loads to compute long-term deflections is identical in both codes.

$$\lambda_{\Delta,steel} = \frac{\xi}{1 + 50\rho'} \tag{3}$$

$$\lambda_{\Delta,GFRP} = 0.6\xi \tag{4}$$

Deflections in GFRP-RC sections will be larger than deflections in similarly-sized sections with steel reinforcement due to the smaller modular ratio of GFRP-to-concrete than steel-to-concrete. Substitution of GFRP for steel on an equal area basis results not only in larger deflections but also in wider crack widths, and is not the philosophy of Code 440.11.

Excessive crack width in both steel-RC and GFRP-RC is undesirable for aesthetic and other reasons that can damage or deteriorate the structural concrete. Acceptable values for crack widths can be relaxed for GFRP-RC as the reinforcement will not corrode. Crack widths less than 0.7 mm are considered acceptable for GFRP-RC in Code 440.11, compared with 0.45 mm for steel-RC in ACI 318. Both codes use an indirect method for controlling crack widths, based on the Gergely-Lutz equation [17], which limits the maximum permitted reinforcing bar spacing, $s_{max}$, as shown in Eq. (5) from ACI 318 and Eq. (6) from Code 440.11.

$$s_{max,steel} = 380\left(\frac{280}{f_s}\right) - 2.5c_c < 300\left(\frac{280}{f_s}\right) \tag{5}$$

$$s_{max,GFRP} = \left(\frac{0.81E_f}{f_{fs}k_b}\right) - 2.5c_c < \left(\frac{0.66E_f}{f_{fs}k_b}\right) \tag{6}$$

where $c_c$ is the clear cover and $f_s$ and $f_{fs}$ are the tensile stress at service loads in the steel and GFRP reinforcement, respectively. Note that ACI 318 permits the service load stress in steel reinforcement to be approximated as two-thirds of the bar's yield strength, but Code 440.11 requires $f_{fs}$ to be computed by an elastic cracked section analysis with the unfactored service moment. Although not apparent from a cursory inspection, Eqs. (5) and (6) are nearly identical after adjusting for differences in the tensile modulus and controlling crack width limits. Note that Eq. (6) explicitly includes the modulus of elasticity of the GFRP reinforcement, $E_f$, unlike Eq. (5) in which the steel modulus is incorporated in the constant. However, the GFRP Eq. (6) includes a coefficient, $k_b$, to account for the degree of bond between the GFRP bar and the surrounding concrete. Shield et al. [18] found $k_b$ values varied between 0.69 and 1.61 based on an examination of available crack width data in the literature. The 1.2 value for $k_b$ specified in Code 440.11 is intended to ensure that crack widths do not exceed 0.7 mm approximately 70% of the time for all GFRP bar surface types. Should the designer believe the maximum allowable crack width should be more restrictive than 0.7 mm, the coefficients applied to $E_f$ in Eq. (6) may be linearly adjusted. In situations where the maximum bar spacing limit given in Eq. (6) yields smaller than practical bar spacing for a given diameter bar, as may be the case for interior slabs, the designer should either consider using a smaller diameter bar to provide the required area of reinforcement or reducing the reinforcement stress by increasing the amount of tensile reinforcement.

Sustained service-load stresses are limited by Code 440.11 to avoid creep-rupture failure in GFRP reinforcement; there is no comparable requirement for steel reinforcement in ACI 318-19. Because service-load stresses will be within the elastic range of the member, they can be calculated using an elastic cracked section analysis. To avoid failure of a GFRP-RC member due to creep rupture, a stress limit of 30% of the GFRP design tensile strength is imposed on the GFRP tensile stress that results from the sustained portion of the service loads. This value of safe sustained-stress level is higher than that recommended in ACI 440.1R-15, as it is based on more recent tests of different size bars from a variety of GFRP manufacturers [19].

Unlike the ACI 318 requirement for strength of flexural members that mandates sections be designed as tension-controlled with the steel yielding before the concrete crushes, Code 440.11 permits both tension-controlled and compression-controlled failures. There is no advantage to using a GFRP-RC tension-controlled section over a compression-controlled section because tension-controlled failures occur by rupture of the GFRP as opposed to a more gradual failure by yielding of the reinforcement that occurs in steel-RC members. Tensile-controlled sections require less GFRP reinforcement than compression-controlled sections, but have higher bar stresses that impact design for crack control and creep rupture. Design assumptions in Code 440.11 are consistent with those in ACI 318-19. The controlling limit state is either by concrete crushing, when the maximum usable strain at the extreme compression fiber attains a value of 0.003, or by GFRP rupture, when the net tensile strain in the extreme layer of GFRP longitudinal reinforcement reaches the design tensile strain. Nominal flexural strength $M_n$ is calculated from first principles using strain compatibility, with the strain in each layer of GFRP considered separately, and internal force equilibrium, with use of the same equivalent stress block for compression-controlled failure modes that was developed for steel-RC and is used in ACI 318. Code 440.11 allows a simplified lower-bound approach based on the equivalent stress block to determine $M_n$ for GFRP-RC sections with tension-controlled failure modes. The form of the calculations for $M_n$ can be determined by comparing the GFRP reinforcement ratio $\rho_f$ to the balanced ratio $\rho_{fb}$.

Flexural resistance factors ($\phi$ factors) in Code 440.11 have been calibrated to maintain a minimum reliability index of 3.5, similar to the reliability index used to calibrate the flexural resistance factor ($\phi = 0.9$) permitted in ACI 318-19 when the net tensile strain in the outermost layer of steel reinforcement in tension is at least 0.005. The Code 440.11 values of $\phi = 0.55$ for GFRP-RC tension-controlled failures (defined as when the net tensile strain in the outermost layer of GFRP reinforcement in tension attains the bars' design rupture strain) and $\phi = 0.65$ for GFRP-RC compression-controlled failures (defined as when the net tensile strain in the outermost layer of GFRP reinforcement is less than 80% of the bars' design rupture strain) reflect the variability in GFRP-RC sections.

### 4.3 Other Major Differences

Design principles for development and bond in GFRP-RC are similar to steel-RC. However, bond mechanisms differ so expressions for GFRP development length differ from steel-RC. For detailing, rather than focusing only on strength, bars also need to be developed to ensure adequate stiffness for serviceability. CODE 440.11 requires development of the bar stress $f_{fr}$ required to achieve nominal strength $M_n$, which for compression-controlled sections is not the full bar strength, $f_{fu}$. Recognizing that flexural design is often controlled by serviceability rather than strength requirements, development lengths can be significantly reduced by use of an $A_{f,req}/A_{f,prov}$ modifier.

Shear strength provided by concrete that is reinforced with GFRP is smaller than shear strength provided by concrete that is reinforced with steel, even though in both cases the expressions for concrete shear strength is assumed to be the shear that causes inclined cracking. The depth to the elastic cracked-section neutral axis in GFRP-RC concrete is smaller than if steel reinforcement is used because of the lower axial stiffness of the GFRP bars. Thus, the shear contribution from the uncracked portion of concrete will be smaller for GFRP-RC. This effect, along with lesser dowel action from GFRP reinforcement, is addressed in ACI CODE 440.11 with revised expressions for the shear contribution of the concrete that are based on the depth of the elastic uncracked section, $k_{cr}d$, rather than the full depth of the concrete section, as shown in Eq. (7). The equation for shear contribution from the concrete $V_c$ includes the same size-effect factor, $\lambda_s$, as in ACI 318-19.

$$V_c = 0.42\lambda_s\sqrt{f_c'}b_w k_{cr}d \tag{7}$$

Shear design for GFRP-RC follows a similar philosophy as for steel-RC except that, unlike with steel stirrups in which failure is assumed to occur when the stirrups yield, the strength of GFRP transverse reinforcement is limited by the bent-bar strength, which is smaller than the straight-bar strength. An additional limit of $0.005E_f$ is also imposed on stirrup stress to ensure that aggregate interlock is maintained.

In the design of GFRP-RC columns the contribution of GFRP in compression is determined by assuming the GFRP has the same compressive strength and stiffness as the surrounding concrete. Tie spacing limits are tightened to account for the reduced stiffness of the reinforcement and lesser ability of the ties to resist buckling of the longitudinal bars. Slenderness limits are more stringent than the limits for steel reinforced columns recognizing that lower modulus GFRP bars make columns more susceptible to slenderness effects.

Only 90-degree hooks are used in GFRP reinforcement. Because GFRP bars do not yield, they also do not unfold under tension so there is little increased benefit to 180-degree hooked bars.

## 5 Future Code 440.11 Revisions

ACI codes typically follow a five-year cycle for update and revision. The anticipated date for the first revision to Code 440.11 is thus 2027. ACI Committee 440 leadership has identified expanded fire-resistance requirements and inclusion of a chapter on design of diaphragms based on validation of available shear friction research as the top priorities for this cycle of Code revision. Other topics likely to be included are lightweight concrete, bundled bars, and shotcrete. Expansion of the Code to include seismic design and prestressed concrete will require significant additional research and these topics are not expected to be covered in the Code in the foreseeable future.

## 6 Conclusion

ACI Committee 440 has published a comprehensive building code covering the use of nonmetallic, GFRP bars in structural concrete. ACI Code 440.11-22 establishes minimum requirements for materials, design, and detailing of RC buildings reinforced with GFRP bars that conform to ASTM D7957-22. GFRP reinforcement has been in use for decades as an alternative to steel reinforcement because of its non-corrosive, non-magnetic, and lightweight properties. With the publication of a long-awaited design standard, it is now possible for model codes and other standards to reference ACI Code-440.11-22, allowing for responsible use of GFRP in concrete construction.

## References

1. ACI Code-440.11-22 (2022) Building code requirements for structural concrete reinforced with GFRP bars and commentary. American Concrete Institute, Farmington Hills, MI
2. ASTM D7957/D7957M-22 (2022) Standard specification for solid round glass fiber reinforced polymer bars for concrete reinforcement. ASTM International, West Conshohocken, PA
3. ACI Code-318.19 (2019) Building code requirements for structural concrete and commentary. American Concrete Institute, Farmington Hills, MI
4. ACI PRC 440.1R-15 (2015) Guide for the design and construction of structural concrete reinforced with FRP bars. American Concrete Institute, Farmington Hills, MI
5. Xian G, Karbhari VM (2007) Segmental relaxation of water-aged ambient cured epoxy. J Polym Degrad Stab 92(9):1650–1659
6. ACI SPEC-440.5-22 (2022) Construction with fiber-reinforced polymer reinforcing bars—specification. American Concrete Institute, Farmington Hills, MI
7. ACI 301-20 (2020). Specifications for structural concrete. American Concrete Institute, Farmington Hills, MI
8. ASTM D7205/D7205M-21 (2021) Standard test method for tensile properties of fiber reinforced polymer matrix composite bars. ASTM International, West Conshohocken, PA
9. ASTM D7617/D7617M-11 (2017) Standard test method for transverse shear strength of fiber-reinforced polymer matrix composite bars. ASTM International, West Conshohocken, PA
10. ASTM D7705/D7705M-12 (2019) Standard test method for alkali resistance of fiber reinforced polymer (FRP) matrix composite bars used in concrete construction. ASTM International, West Conshohocken, PA
11. ASTM D7913/D7913M-14 (2020) Standard test method for bond strength of fiber-reinforced polymer matrix composite bars to concrete by pullout testing. ASTM International, West Conshohocken, PA
12. ASTM D7914/D7914M-21 (2021) Standard test method for strength of fiber reinforced polymer (FRP) bent bars in bend locations. ASTM International, West Conshohocken, PA
13. TMS 402-22 (2022) Building Code Requirements for Masonry Structures. The Masonry Society, Longmont, CO.
14. Brown V (1997) Sustained load deflections in GFRP-reinforced concrete beams. In: Proceedings of the third international symposium on non-metallic (FRP) reinforcement for concrete structures (FRPRCS-3). Japan Concrete Institute, Tokyo, Japan, pp 495–502
15. Hall T, Ghali A (2000) Long-term deflection prediction of concrete members reinforced with glass fiber reinforced polymer bars. Can J Civ Eng 27(5):890–898

16. Walkup SL, Musselman ES, Gross SP (2017) Effect of GFRP compression reinforcement on long- term deflections. In: 13th international symposium on fiber-reinforced polymer reinforcement for concrete structures (FRPRCS-13), Anaheim, CA
17. Gergely P, Lutz LA (1968) Maximum crack width in reinforced concrete flexural members. Causes, mechanism, and control of cracking in concrete, SP-20, American Concrete Institute, Farmington Hills, MI, pp 87–117
18. Shield C, Brown V, Bakis C, Gross S (2019) A recalibration of the crack width bond-dependent coefficient for GFRP-reinforced concrete. ASCE J Compos Constr 23(4)
19. Benmokrane B, Brown V, Mohamed K, Nanni A, Rossini M, Shield C (2019) Creep rupture limit for GFRP bars subjected to sustained loads. ASCE J Compos Constr 23(6)
20. El-Mogy M, El-Ragaby A, El-Salakawy E (2010) Flexural behavior of continuous FRP-reinforced concrete beams. ASCE J Compos Constr 14(6):669–680
21. Mirmiran A, Yuan W, Chen X (2001) Design for slenderness in concrete columns internally reinforced with fiber-reinforced polymer bars. ACI Struct J 98(1):116–125